AFRL-RX-WP-JA-2014-0227

NONCONTACT ACOUSTO-THERMAL EVALUATION OF EVOLVING FATIGUE DAMAGE IN POLYCRYSTALLINE Ti-6Al-4V (POSTPRINT)

S. Sathish and N. Schehl
University of Dayton Research Institute

J. T. Welter and K. V. Jata
AFRL/RXCA

MAY 2014
Interim Report

Distribution A. Approved for public release; distribution unlimited.

See additional restrictions described on inside pages

STINFO COPY

© 2014 AIP Publishing, LLC

AIR FORCE RESEARCH LABORATORY
MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

Copies may be obtained from the Defense Technical Information Center (DTIC) (http://www.dtic.mil).

AFRL-RX-WP-JA-2014-0227 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//Signature//

JOHN T. WELTER, Project Engineer
Materials State Awareness & Supportability Branch
Structural Materials Division

//Signature//

STEPHAN M. RUSS, Chief
Materials State Awareness & Supportability Branch
Structural Materials Division

//Signature//

ROBERT T. MARSHALL, Deputy Chief
Structural Materials Division
Materials and Manufacturing Directorate

This report is published in the interest of scientific and technical information exchange, and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Defense, Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it dows not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) May 2014

2. REPORT TYPE Interim

3. DATES COVERED *(From – To)* 25 June 2009 – 14 April 2014

4. TITLE AND SUBTITLE
NONCONTACT ACOUSTO-THERMAL EVALUATION OF EVOLVING FATIGUE DAMAGE IN POLYCRYSTALLINE Ti-6Al-4V (POSTPRINT)

5a. CONTRACT NUMBER FA8650-09-D-5224-0001

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER 62102F

6. AUTHOR(S)
(see back)

5d. PROJECT NUMBER 4347

5e. TASK NUMBER

5f. WORK UNIT NUMBER X0SU

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
(see back)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command
United States Air Force

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RXCA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RX-WP-JA-2014-0227

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution A. Approved for public release; distribution unlimited. This report contains color.

13. SUPPLEMENTARY NOTES
Journal article published in Journal of Applied Physics 115, (2014). © 2014 AIP Publishing, LLC. The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display or disclose the work. The final publication is available at http://dx.doi.org/10.1063/1.4875098: If authorized, also see AFRL-RX-WP-TR-2014-0218.

14. ABSTRACT
Non-Contact Acousto-Thermal Signature (NCATS) analysis uses conversion of acoustic energy to heat to characterize evolving damage in materials. In the past, the observed temperature changes were interpreted using phenomenological approaches. This paper presents details of the mechanisms and the theoretical models to predict the temperature change due to conversion of acoustic energy to heat. NCATS experimental measurements performed using 20 kHz high amplitude acoustic waves on as received and fatigued polycrystalline Ti-6Al-4V are compared with theoretical calculations based on the mechanisms of transverse thermal currents, inter-crystalline thermal currents, and dislocation density changes. In the as received samples, the transverse thermal currents contribution has been found to be negligible compared with inter-crystalline thermal currents contribution. The experimentally measured maximum temperature change in the as received sample has been found to be 0.5 °C, and the theoretical prediction based on inter-crystalline thermal currents is 0.08 °C. In the fatigue damaged samples, the maximum temperature change increases with increasing damage that can be attributed to the increasing dislocation density. The theoretical prediction of the maximum temperature attained by a sample that is near failure based on dislocation contribution is 2.0 °C, while the experimental measurements have been found to be 0.95 °C. The differences between the theoretical and the experimental measurements are discussed in the context of the uncertainties in several physical parameters used in the theoretical calculations.

15. SUBJECT TERMS
non-contact, acousto-thermal, internal friction, fatigue

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON *(Monitor)*
Unclassified	Unclassified	Unclassified	SAR	10	John T. Welter

19b. TELEPHONE NUBER *(include area code)* (937) 255-9798

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

REPORT DOCUMENTATION PAGE Cont'd

6. AUTHOR(S)

S. Sathish and N. Schehl - University of Dayton Research Institute

J. T. Welter and K. V. Jata - Materials and Manufacturing Directorate, Air Force Research Laboratory, Structural Materials Division

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Dayton Research Institute
Structural Integrity Division
300 College Park Drive
Dayton OH 45469

AFRL/RXCA
Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750

Noncontact acousto-thermal evaluation of evolving fatigue damage in polycrystalline Ti-6Al-4V

S. Sathish,[2] J. T. Welter,[1] N. Schehl,[2] and K. V. Jata[3]
[1]*Materials State Awareness and Supportability Branch (AFRL/RXCA), Air Force Research Laboratory, 2230 Tenth St., Wright-Patterson AFB, Ohio 45433, USA*
[2]*Structural Integrity Division, University of Dayton Research Institute, 300 College Park, Dayton, Ohio 45469, USA*
[3]*Metals Branch (AFRL/RXCM), Air Force Research Laboratory, 2230 Tenth St., Wright-Patterson AFB, Ohio 45433, USA*

(Received 6 November 2013; accepted 14 April 2014; published online 6 May 2014)

Non-Contact Acousto-Thermal Signature (NCATS) analysis uses conversion of acoustic energy to heat to characterize evolving damage in materials. In the past, the observed temperature changes were interpreted using phenomenological approaches. This paper presents details of the mechanisms and the theoretical models to predict the temperature change due to conversion of acoustic energy to heat. NCATS experimental measurements performed using 20 kHz high amplitude acoustic waves on as received and fatigued polycrystalline Ti-6Al-4V are compared with theoretical calculations based on the mechanisms of transverse thermal currents, inter-crystalline thermal currents, and dislocation density changes. In the as received samples, the transverse thermal currents contribution has been found to be negligible compared with inter-crystalline thermal currents contribution. The experimentally measured maximum temperature change in the as received sample has been found to be 0.5 °C, and the theoretical prediction based on inter-crystalline thermal currents is 0.08 °C. In the fatigue damaged samples, the maximum temperature change increases with increasing damage that can be attributed to the increasing dislocation density. The theoretical prediction of the maximum temperature attained by a sample that is near failure based on dislocation contribution is 2.0 °C, while the experimental measurements have been found to be 0.95 °C. The differences between the theoretical and the experimental measurements are discussed in the context of the uncertainties in several physical parameters used in the theoretical calculations. © *2014 AIP Publishing LLC.*
[http://dx.doi.org/10.1063/1.4875098]

I. INTRODUCTION

In materials subjected to repeated mechanical loading, a number of types of damage (plastic deformation, cyclic damage, creep, etc.) may accumulate over time leading to material failure. In polycrystalline metals, even when the load is lower than the average yield stress of the metal, plastic deformation occurs in favorably oriented grains. Cyclic loading with stress lower than the yield stress can increase the number of dislocations and lead to formation of new dislocation structures and substructures (dislocations monopoles, dipoles, vein structures, etc.). When dislocation density reaches a critical value, it can lead to the development of persistent slip bands that can act as a local stress raiser to initiate micro-cracks. The micro-cracks become stress raisers for hastening the growth rate of cracks and eventual failure of the material.[1–5] A number of nondestructive evaluation (NDE) techniques are currently available for routine use for detection of cracks.[6,7] Detecting and quantifying the dimensions of the smallest crack plays an important role in avoiding catastrophic failure before the crack reaches the critical length. Detection and quantification are also useful as important input parameters in models used in the prediction of life of materials and components.[1,8] While NDE for crack detection is a mature methodology, there is a need for NDE methods that can detect and quantify evolving damage. This quantification of evolving damage can provide additional input to life prediction models improving the fidelity of remaining life estimates.

Among the NDE methods sensitive to evolving fatigue damage, methods based on nonlinear acoustics have been extensively investigated.[9–17] Although each of the nonlinear acoustic studies attempt to correlate the nonlinear acoustic parameter to the number of fatigue cycles, only a few investigations have attempted to compare the theoretically evaluated nonlinear acoustic parameter to the accumulating damage through number of fatigue cycles and increasing dislocation density.[9,10,12,17]

Another technique that has been shown to have the potential to detect evolving damage is measuring the change in temperature due to thermo-elastic dissipation during cyclic loading of the sample.[18,19] The change in the temperature of the sample has been found to increase with increasing number of cycles.[20,21] Very little progress has been made in the development of quantitative theoretical models to provide a physical basis for increase in the temperature with increasing fatigue damage, and to be effective the technique requires dynamic loading of the materials and components, which is not always possible.

Sathish *et al.* described a non-contact acousto-thermal signature (NCATS) method.[22] In those experiments, high amplitude longitudinal acoustic waves generated by an acoustic

Distribution A. Approved for public release; distribution unlimited.

horn propagate through an air gap and interact with the sample. An infrared (IR) camera detected and measured the temperature change in the sample caused by conversion of acoustic energy to heat. The rate of change of temperature caused by propagating longitudinal acoustic waves in the material is related to combination of thermal properties, acoustic properties, and the internal friction of the material. A phenomenological relationship between temperature increase and internal fiction has been used to explain observations of NCATS experiments on evolving plastic deformation in Ti-6Al-4V and progressive heat damage in polymer composites.[22–24]

The aim of the present paper is to a provide theoretical basis for NCATS experimental measurements based on examination of multiple mechanisms responsible for internal friction and their contribution to conversion of acoustic energy to heat in polycrystalline Ti-6Al-4V subjected to fatigue damage. The contribution of each of the mechanisms is theoretically calculated and compared with experimental measurements. The comparison of the experimental and theoretical results is discussed with regards to using NCATS as a nondestructive evaluation method for accumulating fatigue damage in metallic materials.

II. THEORY

It is well known that when longitudinal acoustic waves propagate through a homogenous material, a small portion of the acoustic energy is converted into heat, and the rate of change of temperature is

$$\frac{d(\Delta T)}{dt} = \frac{2\pi f}{\rho C_p} Q_T^{-1} \left(\frac{\sigma_m^2}{E}\right), \tag{1}$$

where f (s^{-1}) is the frequency of the acoustic wave, ρ (kg m^{-3}) is the density, C_p (J $kg^{-1}K^{-1}$) is specific heat, E (Pa) is the Young's modulus, σ_m (Pa) is the maximum stress amplitude of the acoustic wave, Q_T^{-1} is the total internal friction, and $\Delta T = (T - T_0)$ is the change in the temperature due to deformation caused by the acoustic wave where T is the temperature during the interaction of the acoustic wave with the sample and T_0 is the initial temperature.[22,25–27]

In materials, a number of internal friction mechanisms acting simultaneously are known to produce dissipation of acoustic energy into heat.[22,25–27] In polycrystalline materials, the average grain size (d) and the thickness of the sample (h) play an important role in internal friction. In NCATS experiments, the acoustic frequency used is approximately 20 kHz, and the approximate wavelength of longitudinal acoustic waves in most metallic materials at this frequency is 300 mm. Sample thickness and the average grain size in the samples used in fatigue experiments presented here are much smaller than the acoustic wavelength at 20 kHz. Under these conditions, internal friction occurs due to diffusion of transverse thermal currents, inter-crystalline thermal currents, and dislocation motion.

A. Internal friction due to transverse thermal currents (Q_{TTC}^{-1})

Transverse thermal currents (TTC) are generated when acoustic stress produces bending motion in the sample. Bending produces compression and tensile stresses on opposing sides of the sample. The temperature of the side in compression is slightly higher than the side in tension. This creates a temperature gradient between the two faces of the sample. Heat diffuses through the thickness from the hotter side to the cooler side, and this process is known as transverse thermal currents. For bending induced by acoustic excitation, the compressive and tensile stresses in the sample are reversed with twice the frequency of the acoustic excitation. Zener has shown that the diffusion of transverse thermal currents leads to a frequency dependent internal friction Q_{TTC}^{-1} described by

$$Q_{TTC}^{-1} = \frac{\alpha_t^2 ET}{\rho C_p} \frac{f.f_{TTC}}{f^2 + f_{TTC}^2}, \tag{2}$$

$$f_{TTC} = \frac{\pi \lambda_{th}}{2h^2 \rho C_P}, \tag{3}$$

where α_t (K^{-1}) is the thermal expansion, λ_{th} (m^2s^{-1}) is the thermal diffusivity, and h (m) is the thickness of the sample.[25]

B. Internal friction due to inter-crystalline thermal currents (Q_{ic}^{-1})

The contribution to internal friction from inter-crystalline thermal currents occurs due to non-uniform heating of individual crystallites during the propagation of acoustic waves in polycrystalline samples. During acoustic wave propagation, every crystallite experiences a uniform, distributed pressure. However, the resulting deformation is not uniform because the crystallites are elastically anisotropic and anisotropic boundary conditions must be satisfied. This leads to variations in deformation over the dimensions of the crystallite. This non-uniform deformation causes measurable temperature gradients to occur in the sample.[25,26] Therefore, the temperature increase due to acousto-thermal interaction with the grain structure is determined by non-uniform distribution of deformation, thermal gradient, and the rate of heat transfer across the grain boundaries. The rate of heat transfer across the grains is known as inter-crystalline thermal flow, and causes a frequency dependent internal friction (Q_{ic}^{-1}). Zener has shown that Q_{ic}^{-1} in a polycrystalline material can be expressed as

$$Q_{ic}^{-1} = \frac{\eta (3\alpha_t)^2 KT}{\rho C_P} \left[\frac{f f_{ic}}{f^2 + f_{ic}^2}\right], \tag{4}$$

$$f_{ic} = \left(\frac{3\pi}{2}\right) \frac{\lambda_{th}}{d^2 \rho C_P}, \tag{5}$$

where η is anisotropic factor defined as fraction of the total strain energy associated with fluctuation of dilation, K (Pa) is the bulk modulus, and d (m) is the average grain diameter in the sample.[25]

C. Internal friction due to dislocation motion (Q_{dis}^{-1})

Dislocation motion during acoustic wave propagation is an important source of internal friction in materials. This is

Distribution A. Approved for public release; distribution unlimited.

especially important in fatigue damage in metals where the evolving fatigue damage increases the dislocation density and changes the dislocation structure. This has significant impact on the frequency and amplitude dependence of the internal friction. Granato and Lücke developed a vibrating string theory of dislocation and derived an expression for internal friction from first principles. The theory for low amplitude acoustic excitation (10^{-8}m–10^{-6}m) predicts that the internal friction depends on the fourth power of the dislocation loop length (L_c) and frequency of excitation (f). At low frequencies (kHz) and low excitation amplitudes, the internal friction can be approximated as

$$Q^{-1}_{IAdisl} = \left[\frac{16Eb^2\Omega}{\pi^4 C^2}\right] B\Lambda L_c^4 f, \tag{6}$$

$$C = \frac{2Gb^2}{\pi(1-\mu)}, \tag{7}$$

where b(nm) is the Burgers vector, μ is the Poisson ratio, Λ (m^{-2}) is the dislocation density, L_c (m) is the average dislocation loop length, B is the damping force per unit length of dislocation per unit velocity (Nms^{-2}), G (Pa) is the shear modulus, and Ω is an orientation or Schmidt factor.[28,29]

They go on to explain at higher amplitudes of excitation ($>10^{-6}$m) the dislocations are unpinned from the pinning centers and move longer distances. Incorporation of the stress required to unpin a dislocation from a defect and the distribution of dislocation loop lengths makes the expression for internal friction much more complex and expressed as

$$Q^{-1}_{HAdisl} = \frac{C_1 C_2}{\varepsilon_0} e^{\left(-\frac{C_2}{\varepsilon_0}\right)}, \tag{8}$$

$$C_1 = \frac{\Omega\Lambda L_N^3}{\pi L_c}\left[\frac{8Eb^2}{\pi^3 C}\right], \tag{9}$$

$$C_2 = \frac{G\kappa b}{4\varsigma E L_c}, \tag{10}$$

where L_N is the average length of dislocation network, κ is the Cottrell misfit parameter, and ζ is a parameter relating shear forces.[28,29]

The expression for high amplitude internal friction can be simplified for low frequency (kHz) acoustic excitation. Assuming that the dislocation loop lengths are equal Bhatia[30] and Mason[31] derived the following expression for the internal friction:

$$Q^{-1}_{HAdisl} = \left[\frac{16\Lambda}{\pi^5}\right]\left[\frac{\varepsilon_c}{\varepsilon_0}\right]^2\left[L_N^2 - L_c^2\right], \tag{11}$$

where L_N is the dislocation network length (m); ε_c is the dislocation unpinning stress, and ε_0 is the strain due to acoustic excitation. In order to determine the temperature change measured on a fatigue damaged sample in the NCATS experiments, the sum of the internal friction contributions from the individual mechanisms of transverse thermal currents, inter-crystalline thermal flow, and dislocation motion have to be included as in Eq. (1).

III. MATERIALS AND METHODS

The specimen used in the present work was extracted from the same batch of Ti-6Al-4V plate that was characterized using electron microscopy.[32] Microscopic examination has shown that it is polycrystalline and has duplex microstructure with an average grain size of 20 μm. It is a dual phase alloy with 60% by volume equi-axed primary α phase and 40% ($\alpha + \beta$) phase. The ($\alpha + \beta$) phase grains have a lamellar structure with alternating platelets of α and β phase. The total content of the α phase in the sample is approximately 95% with the balance being β. The α phase has a hexagonal close pack (HCP) crystal structure, and the β phase has a body center cubic (BCC) structure. Flat dog bone sample geometry was used in the experiments. The overall dimensions of the sample are 150 mm × 30 mm × 2.5 mm with a gage section of 25.4 mm × 12.5 mm × 2.5 mm. The width of the gage section, 12.5 mm, is slightly larger than the diameter of the acoustic horn.

The experimental setup used for measurements is shown in Fig. 1. It consists of: An ultrasonic horn (operating at approximately 20 kHz) to produce high amplitude acoustic waves, a Ti-6Al-4V sample that is cyclically loaded in a servo hydraulic machine to produce fatigue damage, and an infrared (IR) camera that is placed on the opposite side of the sample across from the acoustic horn. A custom developed system and software are used to acquire data from the IR camera and to synchronize the IR camera with the ultrasonic horn. The software is capable of collecting the temperature anywhere in the field of view of the camera. The change in the temperature with time can be collected at a single or multiple points to perform an average over an area in the field of view of the camera.[22]

To experimentally measure the temperature change in the sample due to acoustic interaction, the sample and the horn tip were adjusted to be parallel to each other, and the distance between them was optimized and set to be approximately 300 μm. The grip pressure on the sample was set to zero. The acoustic horn was excited with a 1000 ms long pulse at 100% power of the amplifier (Branson 900BCA). The IR camera was used to capture the temperature changes in the sample over a period of 10 000 ms at a rate of 30 frames per second. The pressure in the grips was increased to the appropriate level, and the sample was fatigued. The

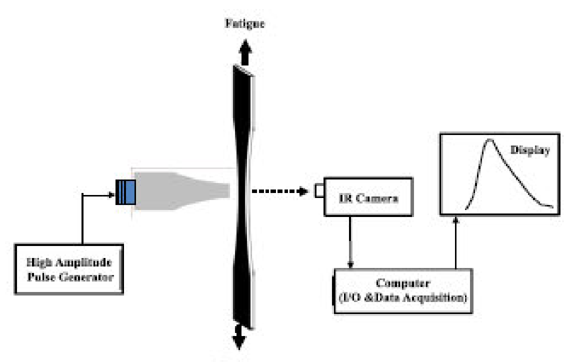

FIG. 1. Block diagram of the NCATS experimental setup.

Distribution A. Approved for public release; distribution unlimited.

sample was cyclically loaded at f = 10 Hz, R = 0.1 with maximum and minimum loads of 4 kN and 0.4 kN, respectively. After 5000 cycles, the cyclic loading was stopped; the grip pressure was reduced to a minimum; the acoustic horn was excited, and time-temperature data was collected. The experimental measurements were repeated at intervals of 5000 cycles until the sample fractured. The out of plane displacement of the sample generated by the acoustic pulse was measured before subjecting the sample to fatigue by using an optical fiber displacement sensor, and it was determined be 10 μm.

IV. RESULTS AND DISCUSSION

Figure 2 shows the change in temperature as a function of time when the sample is subjected to acoustic excitation in the as received condition, after 10 000 fatigue cycles, and after 35 000 cycles of fatigue but before failure. The observed general trend for all cases is that the temperature of the sample rises rapidly, reaches a maximum, and then decreases gradually. It can be seen that the maximum temperature attained by the sample (ΔT_m) increases with increasing number of fatigue cycles.

A. Contribution to temperature change from internal friction due to transverse thermal currents (Q_{TTC}^{-1})

Examination of the experimental configuration (Fig 1) shows that the short sides of the sample are clamped by the grips and the acoustic horn is impinging acoustic stress waves at the center of the sample gage section. This is similar to a vibrating rectangular beam. The acoustic stress could cause a bending in the beam resulting in compression on one side of the sample and tension on the opposite side. Internal friction due to transverse thermal currents in the sample is given by Eq. (2). Using the thermal and elastic properties of Ti-6Al-4V reported in literature[33] in Eq. (2), the internal friction due to transverse thermal currents was evaluated to be

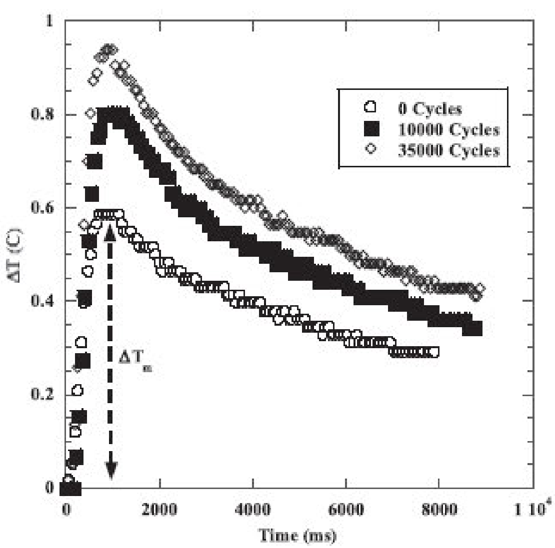

FIG. 2. Time-temperature curves in as received and fatigue damaged Ti-6Al-4V sample.

$Q_{TTC}^{-1} = 5 \times 10^{-8}$. The increase in the temperature of the sample due to transverse thermal current internal friction Q_{TTC}^{-1} was determined using Eq. (1) to be approximately 10^{-5} °C. In comparison with experimental measurements of 0.5 °C to 1.0 °C, temperature change due to Q_{TTC}^{-1} is very small, and it is beyond the detection capability of the IR camera used in the experiments.

The frequency of maximum contribution to internal friction from transverse thermal currents, f_{TTC}, is calculated to be 1.2 Hz using Eq. (3). This is four orders of magnitude smaller than the excitation frequency of 20 kHz used in the experiments. It is expected when the operating frequency is far from the f_{TTC} the internal friction and its contribution to temperature change of the sample to be small. This shows that in the present experiment, the contribution of transverse thermal current to the internal friction and to the overall temperature change may be assumed to be negligible.

B. Contribution to temperature change from internal friction due to inter-crystalline thermal currents (Q_{ic}^{-1})

The average grain size of the Ti-6Al-4V sample used in the experiment is 20 μm. The average grain size is at least 4 orders of magnitude smaller than the acoustic wavelength. The small grain size relative to the acoustic wavelength and the anisotropic physical properties indicate a possibility of significant internal friction due to inter-crystalline thermal currents. Substituting the appropriate physical properties of Ti-6Al-4V and the average grain size into Eq. (5), the frequency of maximum internal friction due to inter-crystalline thermal currents (f_{ic}) was determined to be 20 kHz. The acoustic frequency used in the experiments matches f_{ic}, and the frequency dependent term in the square brackets in Eq. (4) has maximum of 0.5. To determine Q_{ic}^{-1} in the sample using Eq. (4), it is necessary to evaluate the anisotropy factor, η. Zener defined η based on the elastic constants for a cubic crystal.[25] Defining a unique anisotropy factor based on elastic constants in other crystal structures is neither trivial nor consistent.[34–36] As an alternative, Zener suggested that η based on anisotropic thermal expansion in hexagonal crystal structure can be used for evaluation of internal friction due to inter-crystalline thermal currents.[25] Following Zener's approach, η was calculated using experimental measurements of thermal expansion reported in the literature and determined to be 0.03.[25]

The internal friction due to inter-crystalline thermal currents, Q_{ic}^{-1} in the sample was found to be 4×10^{-4}. Its contribution to the rate of change of temperature and the maximum temperature attained by the sample were evaluated using Eq. (1). The rate of change of temperature in the as received sample was determined to be approximately 0.08 °C/s. This leads to a maximum temperature attained due to a 1 s acoustic interaction to be 0.08 °C. The experimentally measured temperature change is approximately six times larger than theoretical calculations. The difference can be attributed to uncertainties in the parameters used in the theoretical calculations. Of all the parameters, the most uncertainty is in the evaluation of η. In hexagonally structured α Ti-6Al-4V, both the thermal expansion and elastic

Distribution A. Approved for public release; distribution unlimited.

moduli are anisotropic, but only the thermal expansion anisotropy has been accounted for in the calculations presented here. It is possible that including the elastic anisotropy contribution will increase the internal friction due to inter-crystalline thermal currents and account for the observed difference. Another possible explanation for the difference is related to the dual phase of the microstructure of Ti-6Al-4V. The lamellar structure of the $(\alpha+\beta)$ grains consists of platelets that are very thin compared to the average grain size. During acoustic excitation, the movement of platelets against each other can generate additional temperature gradients providing an additional contribution to the total internal friction.

C. Contribution to temperature change from internal friction due to dislocation motion (Q_{disl}^{-1})

It is well known[1–5,9,12,32] that the dislocation density in a sample subjected to cyclic loading increases with number of cycles. The change in dislocation density has significant impact on the internal friction.[5,28–31,37,38] The contribution of dislocations to the total internal friction and the time-temperature measurements can be theoretically calculated following Granato and Lücke vibrating string theory.[28,29] Dislocation density and dislocation loop lengths are required to determine the internal friction from the theory. Most often, these terms are determined using transmission electron microscopy (TEM). Maurer studied dislocation density changes using TEM in samples obtained from the same batch of Ti-6Al-4V alloy and subjected fatigue conditions similar to those used in present experiments.[32] Maurer showed that the dislocation density increases from $10^{12}/m^2$ in the as received samples to $10^{15}/m^2$ when a sample fails at 36 000 cycles. It is reasonable to assume that the dislocation densities generated in the present experiments are similar to those measured by Maurer.[32]

In NCATS experiments, a single amplitude of excitation was used, and the sample out of plane displacement was measured to be to be 10 μm. The amplitude dependence of internal friction has been studied extensively in several metallic materials.[2,5,31,39–41] Comparing the range of amplitudes and the internal friction reported for Ti-6Al-4V (Ref. 39) and other metallic materials,[2,5,31,40,41] the amplitude of excitation used in the NCATS experiments can be considered to be high. Thus, it is appropriate to use high amplitude theory to calculate internal friction using Eq. (11). For comparing experimental results with theoretical calculations, the sample subjected to 35 000 cycles where the dislocation density is highest was chosen. It is well known that the dislocation loop length can vary with the fatigue conditions and number of cycles.[2,3,5] Following the approach described by Apple *et al.*,[9] the average loop length can be approximated to be 1 μm. Assuming that the amplitude of the acoustic excitation used in the experiments can unpin dislocations from many pinning centers; it can be further assumed that the maximum dislocation network, L_N, cannot exceed than the average grain size of 20 μm.

Using dislocation density, Maurer obtained from TEM measurements ($\Lambda = 10^{15}\,m^{-2}$),[32] an average dislocation loop length ($L_c = 1\ \mu$m) and dislocation network length of 20 μm into Eq. (11) the Q_{disl}^{-1} was calculated to be 3×10^{-2}. By substituting this value of Q_{disl}^{-1} into Eq. (1), the dislocation motion contribution to the rate of change of temperature in NCATS experiments was found to be approximately 2 °C/s. For an excitation time of 1 s, the maximum change in temperature of the sample is 2 °C.

The combined rate of change of temperature in NCATS experiments for a sample subjected to 35 000 cycles can be evaluated using Eq. (1) with $Q_T^{-1} = Q_{ic}^{-1} + Q_{dis}^{-1}$. Theoretically, $(d\Delta T/dt)$ is determined to be approximately 2.1 °C/s, and the maximum temperature change in the sample due to acoustic excitation of 1 s is 2.1 °C. This is approximately twice the experimental measurement of 0.9 °C. The differences can be attributed to assumptions and approximations made in the theoretical calculation of the internal friction. It is well known that the internal friction in the high amplitude acoustic excitation range is complicated by the zig zag motion, variation of the distance between the dislocation and point defects, density distribution of vacancies, statistical distribution of defects, dislocations network lengths, and loop lengths.[28–31,37–43] Recently, Gremaud and Kustov[42,43] have attempted to develop a complete theory to provide a quantitative comparison with experimental measurements in single crystals of Cu with 30% Ni, and were forced to conclude the improved theory is qualitative as well. In view of these complexities, the results of the theoretical comparison with NCATS experimental measurements presented in the paper are reasonable.

V. CONCLUSIONS

This paper has presented the physical mechanisms responsible for conversion of acoustic energy into heat in the as received and fatigued Ti-6Al-4Vsample in NCATS experiments. The role of the individual internal friction mechanisms of transverse thermal currents, inter-crystalline thermal currents, and dislocation motion, and their contributions to rate of change of temperature ($d\Delta T/dt$) and the maximum temperature change (ΔT_m) are theoretically calculated and compared with NCATS experimental measurements. The contribution of transverse thermal currents in the samples has been found to be negligible, and the inter-crystalline thermal currents contribution is approximately six times smaller than the experimental measurements in as received Ti-Al-4V samples. In samples subjected to fatigue damage (35 000 cycles and near fracture), the contribution of dislocation motion is higher than the other two mechanisms. The experimentally measured total temperature change, ΔT_m, in the fatigue damaged sample is two times smaller than the theoretically calculated contribution from all the three mechanisms. Taking into account the number of assumptions in the theoretical calculations, the agreement between the theoretical calculation and NCATS experimental measurements is considered reasonable.

ACKNOWLEDGMENTS

Portions of this work were performed as USAF Contract FA8650-09-D-5224. The authors wish to thank

Distribution A. Approved for public release; distribution unlimited.

Dr. E. Lindgren and Dr. S. Russ for their critical reading and constructive comments on the manuscript. The authors also wish to thank Mr. E. Klosterman, Mr. R. Reibel, and Mr. T. Boehnlein for their help with the NCATS experimental setup and measurements.

[1]S. Suresh, *Fatigue of Materials* (Cambridge University Press, New York, 2002).

[2]A. Puskar and S. A. Golovin, "Fatigue in materials: Cumulative damage processes," *Material Science Monographs* (Elsevier, New York, 1985).

[3]H. Mughrabi, Fatigue Fract. Eng. Mater. Struct. **22**, 633 (1999).

[4]C. Laird, "The application of dislocation concepts in fatigue," in *Dislocations in Solids*, edited by F. R. N. Nabarro (North Holland, New York, 1983), Vol. 6, pp. 57–120.

[5]J. Pollak, *Cyclic Plasticity and Low Cycle Fatigue Life of Metals* (Academic, Prague, 1991).

[6]*Electromagnetic Testing*, Nondestructive Testing Handbook Vol. 4, edited by P. McIntire (American Society for Nondestructive Testing, Columbus, OH, 1986).

[7]*Ultrasonic Testing*, Nondestructive Testing Handbook Vol. 7, edited by P. O. Moore (American Society of Nondestructive Testing, Columbus, OH, 1986).

[8]F. Ellyin, *Fatigue Damage, Crack Growth and Life Prediction* (Chapman & Hall, New York, 2011).

[9]T. M. Apple, J. H. Cantrell, C. M. Amaro, C. R. Mayer, W. T. Yost, S. R. Agnew, and J. M. Howe, Philos. Mag. **93**(21), 2802 (2013).

[10]J. H. Cantrell and W. T. Yost, Philos. Mag. A **69**, 315 (1994).

[11]J. Frouin, S. Sathish, T. E. Matikas, and J. K. Na, J. Mater. Res. **14**, 1295 (1999).

[12]R. K. Oruganti, R. Sivaramanivas, T. N. Karthik, V. Kommareddy, B. ramadurai, B. Ganesan, E. J. Neiter, M. F. Gigliotti, M. E. Keller, and M. T. Shyamsunder, Int. J. Fatigue **29**, 2032 (2007).

[13]V. V. S. Jaya Rao, E. Kannan, R. V. Prakash, and K. Balasubramaniam, J. Appl. Phys. **104**, 123508 (2008).

[14]J. Y. Kim, L. J. Jacobs, and J. W. Littles, J. Acoust. Soc. Am. **120**, 1266 (2006).

[15]P. B. Nagy, Ultrasonics **36**, 375 (1998).

[16]A. J. Croxford, P. D. Wilcox, B. W. Drinkwater, and P. B. Nagy, J. Acoust. Soc. Am. **126**, EL117 (2009).

[17]J. Frouin, J. Maurer, S. Sathish, D. Eylon, and J. K. Na, in *Proceedings of the 10th World Conference on Titanium* edited by G. Lutjering and J. Albrecht (DGM Wiley-VCH, Hanover, Germany, 2003), Vol. 3, pp.1791.

[18]G. Caglioti, "The thermo-elastic effect: statistical mechanics and thermodynamics of the elastic deformation," in *Mechanical and Thermal Behavior of Metallic Materials*, edited by G. Caglioti and A. F. Milone (North-Holland, New York, 1982).

[19]N. Harwood and W. M. Cummings, *Thermoelastic Stress Analysis* (Adam Hilger, New York, 1991).

[20]H. Rosner, N. Meyndorf, S. Sathish, and T. E. Matikas, *in Nondestructive Methods for Materials Characterization*, edited by G. Y. Baaklini, N. Meyndorf, T. E. Matikas, and R. S. Gilmore, (Mater. Res. Soc. Symp. Proc., 2000), Vol. 591, pp. 73–78.

[21]H. Rosner, "Thermographic nodestructive evaluation of early stages fatigue damage in titanium material," Ph.D. dissertation, (University of Saarlandes, Saarabrucken, Shaker Verlag, Achen Germany, 2003).

[22]S. Sathish, J. T. Welter, K. V. Jata, N. Schehl, and T. Boehnlein, Rev. Sci. Instrum. **83**, 095103 (2012).

[23]J. T. Welter, G. Mallot, N. Schehl, S. Sathish, K. V. Jata, and M. P. Blodgett, AIP Conf. Proc. **1211**, 1397 (2010).

[24]J. Welter, S. Sathish, E. Ripberger, and E. Lindgren, Mater. Eval. **65**, 823 (2007).

[25]C. Zener, *Elasticity and Anelasticity of Metals* (University of Chicago, Chicago, 1948).

[26]L. D. Landau and E. M. Lifshitz, *Theory of Elasticity* (Pergamon Press, New York, 1986).

[27]A. S. Nowick and B. S. Berry, *Anelastic Relaxation in Crystalline Solids* (Academic, New York, 1972).

[28]A. Granato and K. Lücke, J. Appl. Phys. **27**, 583 (1956).

[29]A. Granato and K. Lücke, J. Appl. Phys. **27**, 789 (1956).

[30]A. B. Bhatia, *Ultrasonic Absorption* (Oxford University Press, New York, 1967).

[31]W. P. Mason, *Physical Acoustics and the Properties of Solids* (Van Nostrand, New York, 1959).

[32]J. L. S. Maurer, "Characterization of accumulated fatigue damage in Ti-6Al-4V plate materials using transmission electron microscopy and nonlinear acoustics," Ph.D. dissertation (University of Dayton, Dayton, OH, 2001).

[33]R. Boyer, G. Welsch, and E. Collins, *Materials Properties Handbook: Titanium Alloys* (ASM International, Materials Park, OH, 1994).

[34]S. I. Ranganathan and M. Ostoja-Starzewski, Phys. Rev. Lett. **101**, 055504 (2008).

[35]H. Ledbetter and A. Migliori, J. Appl. Phys. **100**, 063516 (2006).

[36]D. H. Chung and W. R. Buessem, J. Appl. Phys. **38**, 2010 (1967).

[37]*Mechanical Spectroscopy Q^{-1} 2001 with Applications to Materials Science*, edited by R. Schaller, G. Fantozzi, and G. Gremaud (Trans Tech Publications, Enfield, New Hampshire, 2001).

[38]M. S. Blanter, I. S. Golovin, H. Neuhauser, and H. R. Sinning, *Internal Friction in Metallic Materials* (Springer, New York, 2007).

[39]M. C. Jon, W. P. Mason, and D. N. Beshers, J. Appl. Phys. **49**, 5871 (1978).

[40]W. P. Mason and J. Wehr, J. Phys. Chem. Solids **31**, 1925 (1970).

[41]S. Kustov, G. Gremaud, W. Benoit, S. Golyandin, K. Sapozhnikov, Y. Nishino, and S. Asano, J. Appl. Phys. **85**, 1444 (1999).

[42]G. Gremaud and S. Kustov, Phys. Rev. B **60**, 9353 (1999).

[43]G. Gremaud, "Dislocation-point defect interactions," in *Mechanical Spectroscopy Q^{-1} 2001 with Applications to Materials Science*, edited by R. Schaller, G. Fantozzi, and G. Gremaud, (Trans Tech Publications, Enfield, New Hampshire, 2001).

Distribution A. Approved for public release; distribution unlimited.